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Increased reliability for J_0-analysis by QSSPC

Achim Kimmerle[a,*], Philip Rothhardt[a], Andreas Wolf[a], Ronald A. Sinton[b]

[a]*Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany*
[b]*Sinton Instruments, Boulder, CO, USA*

Abstract

This work investigates the influence of physical parameters and of different methods on the analysis of QSSPC measurements with the aim to extract J_0-values of diffused surfaces. We show that the right choice of not only the parameter-set and physical models but also the method is crucial. The comparison with injection dependent simulation data leads to a deviation of up to 34 % from the absolute J_0-value for parameters found in literature. In contrast, the recently implemented method in the WCT-120 lifetime tester software [1] which accounts for band-gap narrowing in the substrate agrees within 3 % over the full range of assumed base doping. Furthermore we show that the carrier-lifetime in the substrate shows a significant influence on J_0-values obtained using the absolute measured recombination and leads to overestimation of up to 50 % even for high base-lifetimes of τ_{SRH} = 1 ms. The implemented parameter-set and analysis method is based on common accepted models and consistent with various simulation tools, and thus allows for the extraction and comparison of injection- and substrate-independent J_0-values.

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Keywords: silicon; lifetime; qsspc; band-gap narrowing; dark saturation current density

1. Introduction

The dark saturation current density J_0 of diffused surfaces is an important parameter to characterize doping techniques and processes for their application in solar cells as well as a central input parameter for solar cell simulation. The common way to obtain such J_0-values is the analysis of the effective excess-carrier recombination lifetime τ_{eff} of symmetrical samples measured with the Sinton Instruments WCT-120 lifetime tester. New models for

* Corresponding author. Tel.: +49-761-4588-5046; fax: +49-761-4588-9250.
E-mail address: achim.kimmerle@fraunhofer.ise.de

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Auger-recombination and intrinsic carrier density n_i have come in use lately and are available as choice in the new Sinton WCT-120 software [1], bringing in question the comparability of published experimental J_0-values and their compatibility with simulation. This work investigates the influence of different methods and physical models on J_0-analysis.

2. Method

2.1. Three different methods for J_0 analysis

Assuming a spatially constant injection density Δn in a symmetrical lifetime sample, the Auger-corrected effective lifetime τ_{corr} can be described by [2]

$$\frac{1}{\tau_{corr}} = \frac{1}{\tau_{eff}} - \frac{1}{\tau_{intr}} = \frac{2J_0}{qW}\frac{N_{A,D} + \Delta n}{n_{i,eff}^2}, \tag{1}$$

with the substrate thickness W, the elementary charge q, the base doping density $N_{A,D}$ and the intrinsic carrier density n_i. Throughout this work J_0 represents the recombination parameter of one side of the wafer.

One method to extract the J_0-value of diffused surfaces on symmetrical samples from the measured Auger-corrected effective lifetime is differentiating Eq. 1 with respect to Δn, assuming the SRH-contribution to the base lifetime to be non-injection dependent. Historically, band-gap narrowing (BGN) in the substrate is neglected leading to a non-injection dependent n_i and thus [2]

$$J_0 = \frac{1}{2} qW n_i^2 \frac{\mathrm{d}}{\mathrm{d}\Delta n}\left(\frac{1}{\tau_{corr}}\right), \tag{2}$$

In the case of an injection dependent n_i, here denoted as effective carrier density $n_{i,eff}$, the differentiation leads to [1]

$$J_0 = \frac{1}{2} qW \frac{\mathrm{d}}{\mathrm{d}\Delta n}\left(\frac{n_{i,eff}^2}{\tau_{corr}}\right). \tag{3}$$

This second method was recently implemented in the Sinton WCT-120 software [1] and is available as choice in the latter. The injection dependence of n2i,eff in Eq. 2 cannot be neglected in the case of use of a BGN model. A third method is to calculate the J0-value from the total recombination at one given injection density by [3]

$$J_0 = \frac{1}{2}\frac{n_{i,eff}^2}{N_{A,D} + \Delta n} \cdot \frac{qW}{\tau_{corr} - \frac{W^2}{D\pi^2}} \tag{4}$$

with the minority carrier diffusion constant D.

2.2. Applied parameters

Physical input parameters needed for J0-analysis of lifetime measurements are the intrinsic carrier density in the substrate ni and the intrinsic lifetime □i. In literature different values for these parameters are used. For the intrinsic lifetime there are 3 common models: The Sinton-model for the Auger recombination at high injection levels, the

model by Kerr et al. [4] and the model by Richter et al. [5]. The Richter model is very similar to the Kerr model but predicts higher lifetimes for n-type base material. It is based on new experimental data and commonly accepted as the most accurate model for intrinsic base recombination.

In order to obtain a J0-value that is solely a property of the diffused region one has to apply a ni-model that accounts for BGN in the substrate. In this work we compare 2 different assumptions for ni that are commonly used in literature: ni = 8.599x109 cm-3, the standard implementation in the lifetime tester here denoted as ni-Sinton. The second model accounting for BGN [6] is implemented in the new Sinton-WCT software [1, 7]. It is similar to the models used in modern simulation tools such as EDNA [8], Sentaurus TCAD [9] and cmd-PC1D 6.0 [10] and was used for the Auger-model by Richter et al. Since the Sinton models for Auger-recombination and ni are chosen carefully to be in combination consistent with experimental data they can't be combined in a meaningful way with the other models.

The temperature dependence of ni,eff is nearly independent from doping or injection density and J0/ni,eff2 is approximately independent from temperature, thus J0-values of different temperatures can be easily converted via J0(300K) = 1.361•J0(25°C). This relation is accurate to 0.2 % for the investigated samples according to the applied model. In this work, 25°C is applied.

2.3. Simulation and experimental setup

To compare the influence of different methods and models on the J_0-analysis we create data sets of effective lifetime τ_{eff} over average injection density n_{av} for symmetric lifetime samples assuming J_0-values of 100 fA/cm^2 or 20 fA/cm^2 using the simulation software QsCell 5.7 [11]. We chose the Richter model for intrinsic recombination, the implemented flasher spectrum for excitation and apply the $n_{i,eff}$ model that accounts for injection dependent BGN in the substrate. Throughout this work, these two models are applied if not denoted differently. We then extract the J_0-values using the different analysis methods. For the analysis shown here, no additional recombination apart from Auger-recombination and effective surface recombination is assumed. Furthermore symmetric lifetime samples (float-zone-Si material, W = 200 - 230 µm) of different base-doping were produced with alkaline textured surfaces, exposed to the same industrial-type $POCl_3$-diffusion (resulting in a sheet resistance of ~ 90 Ω/sq.) and SiN_x passivation procedure. The samples were analysed in a Sinton WCT-120 lifetime tester. All experimental and simulated data sets are analysed in the injection range of $3•10^{15}$ cm^{-3} ± 30%.

3. Results

3.1. Influence of analysis type and models

Simulation

Eq. 2 leads to a substrate dependent J_0 for constant n_i-values (Fig. 1). For n_i values depending on the substrate but neglecting BGN due to injection a nearly constant J_0 that is 10 % lower than the input-value is observed. The application of Eq. 2 together with a mean value of $n_{i,eff}$ over the fit-range $n_{i,mean\text{-}fit}$ improves the J_0-analysis, but still deviates more than 5% from the input-value. In contrast, Eq. 3 leads to a very good description of J_0 over the whole range of substrate doping (note that the same model for n_i and BGN is applied in the simulation and the analysis with Eq. 2 $n_{i,0}$ and $n_{i,mean\text{-}fit}$, Eq. 3 and Eq. 4). This leads to the conclusion that the change in $n_{i,eff}^2$ over the fit-range due to BGN influences the slope of the inverse lifetime curve significantly – ignoring this (Eq. 2) means interpreting it as part of the J_0-value. This shows that the traditional analysis Eq. 2 leads to an effective J_0-value that depends on the substrate and fit-range and is not applicable in simulation tools that account for BGN.

The application of the Auger model by Kerr in Eq. 3 leads to a deviation of up to 5 % for the J_0 = 100 fA/cm^2 and 10 % for the J_0 = 20 fA/cm^2 data-sets, pointing out that the use of a commonly accepted Auger-model is crucial for the comparison of low J_0-values, especially on n-type base material.

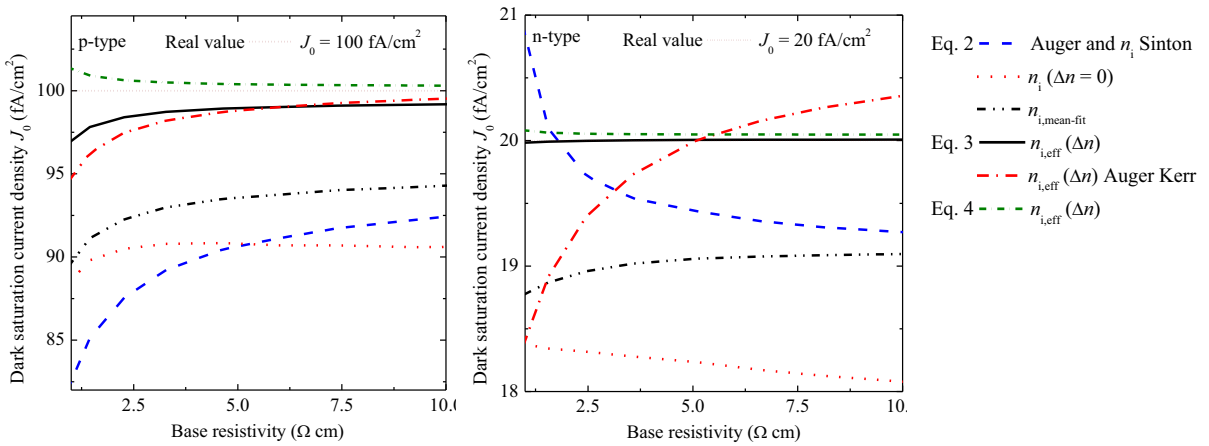

Fig. 1. J_0-values extracted from simulation data with the different methods and models. The data was simulated with p-type base doping for J_0 = 100 fA/cm^2 (left) and n-type base doping for J_0 = 20 fA/cm^2 (right).

In literature, there can be found further constant values of n_i applied for the J_0-analysis such as $n_i = 10^{10}$ cm^{-3}, this leads to an overestimation of the J_0 for the investigated simulation of up to 35 % (not shown in Fig 1).

Measurement

The inverse of the measured Auger-corrected lifetime (Fig. 2) shows reasonable linear behaviour. Nevertheless, the BGN-corrected curves used in Eq. 3 improve linearity over a wide range and exhibit different slopes, resulting in different extracted J_0-values (Table 1). For comparison, J_0-values are given calculated with Eq. 2, applying a mean value of $n_{i,eff}$ over the fit-range $n_{i,mean-fit}$. This shows, consistent with the simulation data, that the change in $n_{i,eff}$ influences the slope significantly. Even for the highly doped n-type material where the analysis takes place at an injection density lower than the doping density, Eq. 3 leads to a good accordance with the J_0-values measured on the lowly doped samples. However, the highly doped p-type material leads to a significant difference, pointing out that at the presence of significant SRH-recombination in the base, lowly doped samples should be used to exceed the doping density in the fit.

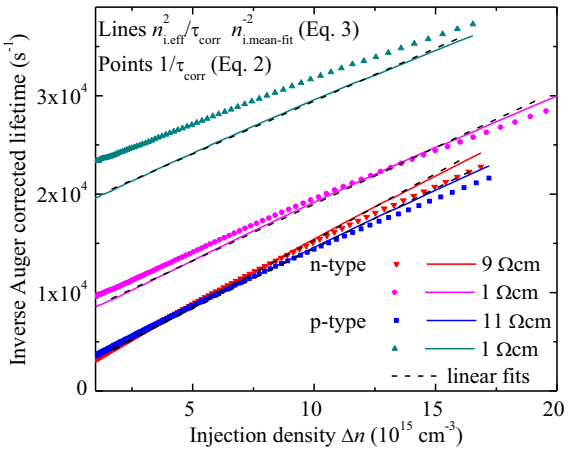

Fig. 2. Measured Auger-corrected inverse lifetime over excess carrier density used for Eq. 1 and BGN-corrected curves (scaled to a mean value $n_{i,mean-fit}$) used for Eq. 2 (dashed straight lines are guide to the eye to show linearity).

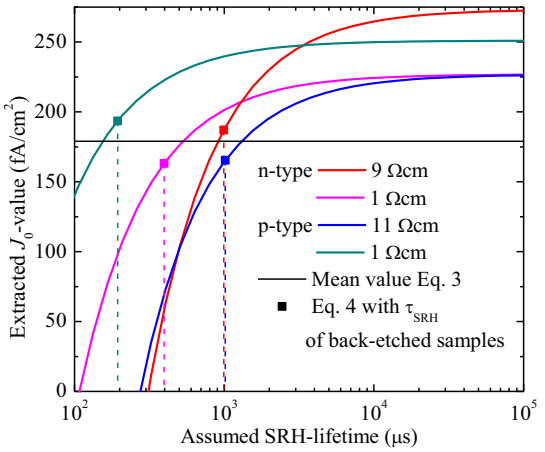

Fig. 3. Resulting J_0-values using Eq. 4 at $\Delta n = 10^{15}$ cm^{-3} for different assumed SRH-recombination. Points show the measured Auger corrected base lifetime after emitter etch-back and passivation.

3.2. J_0-analysis from absolute recombination

Calculating J_0 from the absolute recombination via Eq. 4 leads to a very good accordance with the input data of the simulation (Fig. 1). However, while in simulation the base lifetime is known exactly, this is not the case for any experiment. Assuming no significant reduction in base-lifetime further than Auger-recombination leads to a clear overestimation of J_0 (Table I) by Eq. 4 for the measured samples. After removing the emitter and passivating the samples again, the Auger-corrected lifetime of the samples was measured. It is observed that although the lifetime of some samples seems reasonable high, it strongly affects the J_0-analysis with Eq. 4 (Fig. 3). The sensitivity of the method to an additional recombination strongly depends on the Auger-lifetime and thus on the base doping: While in highly doped samples (high Auger-recombination) it seems possible to reach only small deviations for reasonable high J_0-values (in this example, $\tau_{SRH} \approx 1$ ms would be required for a overestimation of J_0 of ~18 fA/cm^2, here 10 % on a 1 Ω cm p-type substrate), for lowly doped samples a very high material quality seems to be required. Thus Eq. 4 can only be recommended if the use of highly doped base material for symmetrical lifetime samples is unavoidable or the lifetime of the base substrate is known.

Table 1. J_0-values after different methods (fA/cm^2). The applied fit-range is 3 10^{15} cm^{-3}± 30 %. Auger corrected lifetime τ_{SRH} after back-etching of emitter and subsequent passivation (@ $\Delta n = 10^{15}$ cm^{-3}).

Base doping	Eq. 2: n_i and Auger Sinton	Eq. 2: $n_{i,mean-fit}$	Eq. 3	Eq. 4 ($\tau_{SRH} = 0$)	Eq. 4 (τ_{SRH} measured)	τ_{SRH}
Phosphorus, 1 Ω cm	157	161	184	227	163	397 µs
Phosphorus, 9 Ω cm	161	169	183	273	187	994 µs
Boron, 1 Ω cm	133	135	168	251	194	194 µs
Boron, 11 Ω cm	158	167	182	227	165	1017 µs

4. Summary

It is shown that not only the physical models but also the analysis method has a significant influence on the results of J_0-analysis of symmetrical lifetime samples. The recently implemented analysis in the Sinton WCT-120 software leads to very good accordance with simulation data and allows the comparison of measurements on different substrates as well as the application of the results in modern simulation tools. The comparison with the formerly used method shows an improvement on the reproduction of J_0-values on simulated measurements, using

state-of-the-art physical models. On measurement data, the new analysis method extends the accessible injection-range due to a significant reduction of the often observed bend in the inverse corrected lifetime curves. The J_0-analysis from absolute recombination turns out to be sensitive even for small reductions in base-lifetime. Thus the authors recommend strongly the usage of the recently implemented method and of moderately to lowly doped base-material.

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